

# Separate seesaw and its applications to dark matter and baryogenesis

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## Abstract

We propose a new seesaw model in an extra-dimensional setup where only right-handed neutrinos are bulk fields. In the model, localizations of an extra-dimensional wave function and brane Majorana mass of the right-handed neutrinos can be different among each generation of the right-handed neutrinos. The setup can lead to different suppression factor dependences of effective right-handed neutrino masses and neutrino Yukawa couplings for each generation. It is shown that the resultant mass spectra of the right-handed neutrinos and neutrino Yukawa couplings are favored in models of neutrino dark matter with baryogenesis.

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## 1 Introduction

Results from neutrino experiments have established a phenomenon of neutrino oscillations. The experimental data can be nicely understood by three flavor mixings of active neutrinos and described by three mixing angles, one CP-phase, and two mass squared differences of the active neutrinos. The non-zero masses of the active neutrinos require a physics beyond the standard model (SM). In addition, one has to explain a smallness of the active neutrino mass scales. One of famous explanations to realize the small active neutrino masses is the seesaw mechanism [1]. There are several types of the seesaw mechanism. In the canonical type I seesaw mechanism, heavy right-handed (sterile) neutrinos are introduced into the SM as Majorana particles. After decoupling the heavy right-handed neutrinos, the small active neutrino masses can be realized. Furthermore, it is well known that decays of such heavy Majorana (right-handed) neutrinos can also generate the baryon asymmetry of the Universe (BAU), so-called leptogenesis [2].

In addition to the leptogenesis, the right-handed (sterile) neutrinos can also play a cosmological role, which is dark matter (DM) [3] candidate. If the mass of the sterile neutrino

is in the keV range, the sterile neutrino can serve the DM [4, 5] (see also [6, 7]) and such kind of sterile neutrino DM model is constrained by cosmological and astrophysical observations [6, 8, 9, 10]. There are also some investigations of astrophysical phenomena [10, 11] and related considerations for the keV sterile neutrino DM (e.g. see [13, 14, 15, 16, 17]). One of interesting discussions about the keV sterile neutrino DM is to give simultaneous explanations for problems in particle physics and cosmology such as the smallness of the active neutrino masses, the origin of BAU, and LSND/MiniBooNE anomaly [18] in addition to the DM [12, 15, 16, 17]. However, such kind of models to simultaneously explain several problems require strongly hierarchical mass spectra of the sterile neutrinos and an additional suppression for a left-right mixing of the keV sterile neutrino in the context of the seesaw mechanism. A split seesaw [15]<sup>1</sup> and the Froggatt-Nielsen mechanism [19] can naturally realize strongly hierarchical mass spectra of the right-handed neutrinos [14] but do not give the additional suppression of the left-right mixing without taking the corresponding neutrino Yukawa coupling to be small enough to satisfy a cosmological bound. In the split seesaw mechanism, an essential point to obtain hierarchical mass spectra comes from properties of wave function in an extra-dimension.

Extra-dimensional theory is one of fascinating approaches to afford a compelling solution to a gauge hierarchy problem [20]. In fact a discovery of an evidence of extra-dimension(s) in addition to the Higgs particle and supersymmetry is one of missions in the Large Hadron Collider experiment. Further, extra-dimensional theories can also give rich phenomenologies such as alternatives to the electroweak (EW) symmetry breaking mechanisms in the SM (e.g. see [21, 22]), to give DM candidates [23, 24], deviations of coupling constants from the standard ones [22, 25], and realizations of fermion mass hierarchies [24, 26] and the smallness of the active neutrino mass [27], etc.. In this work, we will propose a new model with the right-handed neutrinos in an extra-dimensional space and apply it to models of keV sterile neutrino DM with baryogenesis mechanism. Then, it will be shown that the new seesaw can be favored in the DM models with respect to a realization of the additional suppression for the left-right mixing.

The paper is organized as follows: In section 2, brief reviews of the canonical type I seesaw and the split seesaw mechanisms are given. In section 3, we discuss all possible localizations of the right-handed neutrinos and Majorana masses in an extra-dimensional space-time, and show the results for relevant parameters to the neutrino masses. In section 4, a new seesaw model from the extra-dimension is proposed. In section 5, we apply the new seesaw to models of the neutrino DM with baryogenesis mechanism. Section 6 is devoted to the summary.

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<sup>1</sup>See also [16] for a consideration of  $A_4$  flavor models in the split seesaw mechanism.

## 2 Seesaw mechanisms

### 2.1 Type I seesaw mechanism

Relevant Lagrangian for the type I seesaw mechanism [1] reads

$$\mathcal{L} = i\overline{\nu_{Ri}}\gamma^\mu\partial_\mu\nu_{Ri} - \left( (y_\nu)_{i\alpha}\overline{\nu_{Ri}}L_\alpha\phi + \frac{(M_R)_{ij}}{2}\overline{\nu_{Ri}^c}\nu_{Rj} + \text{h.c.} \right), \quad (1)$$

where  $\nu_{Ri}$  ( $i=1,2,3$ ) are the right-handed neutrinos,  $L_\alpha$  ( $\alpha = e, \mu, \tau$ ) are left-handed lepton doublets,  $\phi$  is the SM Higgs,  $y_\nu$  is a neutrino Yukawa coupling matrix,  $M_R$  is a Majorana mass matrix of the right-handed neutrinos, and  $\mu = 0, 1, 2, 3$ , respectively. Here we have introduced three generations of the right-handed neutrinos to the SM. After integrating out the right-handed neutrinos, a mass matrix of light (active) neutrinos is given by

$$M_\nu \simeq y_\nu^T M_R^{-1} y_\nu v^2, \quad (2)$$

where  $v$  is a vacuum expectation value (VEV) of the Higgs. This type I seesaw mechanism with heavy Majorana masses of the right-handed neutrinos can lead to small active neutrino masses without tiny neutrino Yukawa couplings.

### 2.2 Split seesaw mechanism

Next, let us show a seesaw model in an extra-dimension. The seesaw model is known as the split seesaw mechanism [15]. The split seesaw has been considered in a flat 5D space-time compactified on an orbifold  $S^1/Z_2$  with the 5D coordinate,  $y \equiv x^5$ . A fundamental region of the orbifold is given by  $y \in [0, \ell]$ . The orbifold gives two fixed points and one can consider branes at the fixed points. One of the branes ( $y = 0$ ) is a SM brane where the SM particles reside, while the other ( $y = \ell$ ) is a hidden brane.

Then three generations of Dirac spinor,  $\Psi_i(x, y) = (\chi_i(x, y), \bar{\psi}_i(x, y))^T$ , are introduced on the bulk with bulk masses  $m_i$  in this flat 5D setup. A fundamental action for the 5D Dirac spinor is

$$S = \int d^4x \int_0^\ell dy M (i\bar{\Psi}_i \Gamma^A \partial_A \Psi_i + m_i \bar{\Psi}_i \Psi_i), \quad A = 0, 1, 2, 3, 5, \quad (3)$$

where  $M$  is a 5D fundamental scale and we assume that the 5D Dirac mass matrix  $m$  is diagonal ( $m_i \equiv m_{ii}$ ) for simplicity. The 5D gamma matrices  $\Gamma^A$  are defined by

$$\Gamma^\mu = \begin{pmatrix} 0 & \sigma^\mu \\ \bar{\sigma}^\mu & 0 \end{pmatrix} \quad \text{and} \quad \Gamma^5 = -i \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix}. \quad (4)$$

Note that a mass dimension of  $\Psi_i(x, y)$  is  $3/2$ . Zero modes of  $\Psi_i(x, y)$  follow Dirac equations as

$$(i\Gamma^5\partial_5 + m_i)\Psi_i^{(0)}(x, y) = 0. \quad (5)$$

Solutions of the 5D Dirac equations determine wave function profiles of the zero modes on the bulk as  $e^{\mp m_i y}$  for  $\chi_i(x, y)$  and  $\bar{\psi}_i(x, y)$ . In order to obtain chiral fermions in 4D, the fields are transformed under an orbifold parity as

$$Z_2 : \Psi_i(x, y) \rightarrow P\Psi_i(x, y) = +\Psi_i(x, y), \quad (6)$$

where  $P = -i\Gamma_5$ . Under this orbifold parity, only  $\bar{\psi}_i(x, y)$  can have a zero mode. Note that the bulk masses  $m_i$  have to carry negative  $Z_2$  parity to make the fundamental action invariant under the above parity transformation. After canonical normalization of the Dirac fermions in 4D, the zero modes of  $\Psi_{R_i}(x, y) \equiv (0, \bar{\psi}_i(x, y))^T$  are represented by normalized field  $\psi_{R_i}^{(0)}(x)$  as

$$\Psi_{R_i}^{(0)}(x, y) = \sqrt{\frac{2m_i}{(e^{2m_i\ell} - 1)M}} e^{m_i y} \psi_{R_i}^{(0)}(x), \quad (7)$$

where  $\psi_{R_i}^{(0)}(x)$  are identified with the right-handed neutrinos in 4D,  $\psi_{R_i}^{(0)} = \nu_{R_i}$ . A point is that the 5D wave function profiles of  $\Psi_{R_i}^{(0)}(x, y)$  with real positive (negative)  $m_i$  localize at the hidden (SM) brane since the profile is described by the exponential function,  $e^{m_i y}$ . Therefore, the right-handed neutrinos,  $\psi_{R_i}^{(0)} (= \nu_{R_i})$ , have exponentially suppressed Yukawa couplings at the SM brane when  $m_i\ell \gg 1$  with real positive  $m_i$ .

The split seesaw mechanism utilizes the above property of the wave function profiles of the right-handed neutrinos. Relevant Lagrangian for the split seesaw mechanism is given by

$$S = \int d^4x \int_0^\ell dy \left[ M \left( i\bar{\Psi}_{R_i}^{(0)} \Gamma^A \partial_A \Psi_{R_i}^{(0)} + m_i \bar{\Psi}_{R_i}^{(0)} \Psi_{R_i}^{(0)} \right) - \delta(y) \left( (\tilde{y}_\nu)_{i\alpha} \bar{\Psi}_{R_i}^{(0)} L_\alpha \phi + \frac{(\tilde{M}_R)_{ij}}{2} \bar{\Psi}_{R_i}^{(0)c} \Psi_{R_j}^{(0)} + \text{h.c.} \right) \right]. \quad (8)$$

Inserting (7) into (8), we can obtain effective 4D Majorana mass matrix of the right-handed neutrinos and neutrino Yukawa coupling matrix as

$$(M_R)_{ij} = f_i f_j (\tilde{M}_R)_{ij}, \quad (9)$$

$$(y_\nu)_{i\alpha} = f_i (\tilde{y}_\nu)_{i\alpha}, \quad (10)$$

respectively, where

$$f_i \equiv \sqrt{\frac{2m_i}{(e^{2m_i\ell} - 1)M}}. \quad (11)$$

It is convenient for the following discussion to define a diagonal matrix  $F$  as  $F_{ij} \equiv \delta_{ij} f_j$ . The effective 4D Majorana mass matrix of the right-handed neutrinos and the neutrino Yukawa

coupling matrix given in (9) and (10) are rewritten by the use of  $F$ ,

$$M_R = F\tilde{M}_R F, \quad (12)$$

$$y_\nu = F\tilde{y}_\nu. \quad (13)$$

The seesaw mechanism leads to

$$M_\nu = y_\nu^T M_R^{-1} y_\nu v^2 = \tilde{y}_\nu^T \tilde{M}_R^{-1} \tilde{y}_\nu v^2. \quad (14)$$

for the mass matrix of the light neutrinos. Note that the factor  $f_i$  are completely canceled out in the seesaw mechanism. This is one of interesting features of the split seesaw mechanism.

The most important feature of the mechanism is as follows: By taking appropriate values for  $m_i$ , we can obtain strongly hierarchical mass spectra of the right-handed neutrinos and the neutrino Yukawa matrix elements shown in (9) and (10) due to the exponential suppression in  $f_i$  without introducing strongly hierarchical mass scales in the model. For instance, if one takes  $(m_1\ell, m_2\ell, m_3\ell) \simeq (23.3, 3.64, 2.26)$ ,  $M = 5 \times 10^{17}$  GeV,  $\ell^{-1} = 10^{16}$  GeV,  $(\tilde{M}_R)_{ii} = 10^{15}$  GeV in a diagonal basis of  $\tilde{M}_R$ , we can obtain a splitting mass spectrum of the right-handed neutrinos including both keV and intermediate mass scales as

$$(M_1, M_2, M_3) = (5 \text{ keV}, 10^{11} \text{ GeV}, 10^{12} \text{ GeV}), \quad (15)$$

in the 4D effective theory. In the case, mass scales in the fundamental action are super heavy as  $\mathcal{O}(10^{15-17})$  GeV or the EW scale  $\mathcal{O}(10^2)$  GeV, and the tiny active neutrino mass scale can be realized by the seesaw mechanism without tiny neutrino Yukawa couplings. Further, the lightest sterile neutrino with the keV mass can be a candidate for the DM and heavier sterile neutrinos with the masses of  $\mathcal{O}(10^{11-12})$  GeV can lead to the BAU via leptogenesis.

### 3 Localizations of right-handed neutrinos and Majorana masses

#### 3.1 Localized right-handed neutrinos at hidden brane and Majorana masses at SM brane

In the previous section, we have presented a brief review of the split seesaw mechanism. In the mechanism, the 5D wave functions of the right-handed neutrinos exponentially localize at the hidden brane (7), and the Majorana masses of the right-handed neutrinos are localized at the SM brane (8). As the results, one can easily obtain strongly hierarchical mass spectra of the right-handed neutrinos and the neutrino Yukawa couplings without introducing strongly hierarchical mass scales in the fundamental action. For the resultant active neutrino mass

after the seesaw mechanism, it is given by the same formula as the one in the type I seesaw mechanism. These setup and results are summarized as

$$\begin{cases} \Psi_{R_i}^{(0)}(x, y) = f_i e^{m_i y} \psi_{R_i}^{(0)}(x) & \text{for the localization of the 5D wave functions} \\ S \supset -\delta(y) \frac{(\tilde{M}_R)_{ij}}{2} \bar{\Psi}_{R_i}^{(0)c} \Psi_{R_j}^{(0)} & \text{for the localization of the Majorana mass matrix} \end{cases}, \quad (16)$$

and

$$\begin{cases} (M_R)_{ij} = f_i f_j (\tilde{M}_R)_{ij} & \text{for the 4D Majorana mass matrix} \\ (y_\nu)_{i\alpha} = f_i (\tilde{y}_\nu)_{i\alpha} & \text{for the 4D neutrino Yukawa coupling matrix} \\ M_\nu = \tilde{y}_\nu^T \tilde{M}_R^{-1} \tilde{y}_\nu v^2 & \text{for the light (active) neutrino mass matrix} \end{cases}, \quad (17)$$

with the suppression factors  $f_i$  (if  $m_i \ell \gg 1$ ), respectively. We call this case as  $(\Psi_R^{(0)}, \tilde{M}_R) = (H, S)$  where “ $H$ ” and “ $S$ ” mean that the 5D wave function ( $\Psi_R^{(0)}$ ) or Majorana mass ( $\tilde{M}_R$ ) of the right-handed neutrinos localizes at the hidden and SM branes, respectively. Therefore, note that the other three possibilities of localizations ( $(\Psi_R^{(0)}, \tilde{M}_R) = (S, H)$ ,  $(H, H)$ , and  $(S, S)$ ) can be generically considered. In the following sections, we investigate the other three localizations and their results.

### 3.2 Localized right-handed neutrinos at SM brane and Majorana masses at hidden brane

The split seesaw mechanism assumes  $(H, S)$  localizations, namely the 5D wave functions of the right-handed neutrinos localize at the hidden brane while the Majorana mass matrix localizes at the SM brane. Here we consider the reverse situation as  $(\Psi_R^{(0)}, \tilde{M}_R) = (S, H)$ , i.e. the 5D wave functions of the right-handed neutrinos localize at the SM brane while the Majorana mass matrix localizes at the hidden brane. The localization of 5D wave function of the right-handed neutrinos is determined by a sign for the bulk mass in (3). Therefore, if one take minus sign for the bulk mass unlike the case of the split seesaw mechanism  $(H, S)$ , one can obtain a 5D wave function profile described by  $e^{-m_i y}$  for the zero mode of the right-handed neutrinos. In the case, after the normalization, the  $\Psi_{R_i}^{(0)}(x, y)$  is written as

$$\Psi_{R_i}^{(0)}(x, y) = \sqrt{\frac{2m_i}{(1 - e^{-2m_i \ell})M}} e^{-m_i y} \psi_{R_i}^{(0)}(x) \equiv g_i e^{-m_i y} \psi_{R_i}^{(0)}(x). \quad (18)$$

Note that the factor  $g_i$  is not exponential suppression one if  $m_i \ell \gg 1$  unlike the  $f_i$  in the split seesaw mechanism. Therefore, the right-handed neutrinos couple to the SM particles without any exponential suppressions.

For the localization of the Majorana mass matrix at the hidden brane, the relevant action

becomes

$$S = \int d^4x \int_0^\ell dy \left[ M \left( i \overline{\Psi_{R_i}^{(0)}} \Gamma^A \partial_A \Psi_{R_i}^{(0)} - m_i \overline{\Psi_{R_i}^{(0)}} \Psi_{R_i}^{(0)} \right) - \left( \delta(y) (\tilde{y}_\nu)_{i\alpha} \overline{\Psi_{R_i}^{(0)}} L_\alpha \phi + \delta(y - \ell) \frac{(\tilde{M}_R)_{ij}}{2} \overline{\Psi_{R_i}^{(0)c}} \Psi_{R_j}^{(0)} + \text{h.c.} \right) \right]. \quad (19)$$

After substituting (18) into (19), one can obtain the 4D Majorana mass matrix of the right-handed neutrinos and the 4D neutrino Yukawa coupling matrix as

$$(M_R)_{ij} = g_i g_j e^{-(m_i+m_j)\ell} (\tilde{M}_R)_{ij} = f_i f_j (\tilde{M}_R)_{ij}, \quad (y_\nu)_{i\alpha} = g_i (\tilde{y}_\nu)_{i\alpha}, \quad (20)$$

respectively where a relation  $f_i = g_i e^{-m_i \ell}$  is utilized. By taking the matrix forms as (9) and  $y_\nu = G \tilde{y}_\nu$  with  $G_{ij} \equiv \delta_{ij} g_i$ , the seesaw mechanism leads to  $M_\nu = \tilde{y}_\nu^T E \tilde{M}_R^{-1} E \tilde{y}_\nu v^2$  where  $E \equiv G F^{-1} = F^{-1} G$  and  $E_{ij} = \delta_{ij} e^{m_i \ell}$ .

We can find that the 4D Majorana masses of the right-handed neutrinos are exponentially suppressed from a fundamental scale  $\tilde{M}_R$  like the split seesaw mechanism. Therefore, strongly hierarchical mass spectra of the right-handed neutrinos can be also realized without introducing strongly hierarchical mass scales for the right-handed neutrinos. On the other hand, the neutrino Yukawa couplings are not suppressed unlike the split seesaw case. As the results, a fundamental mass scale of active neutrino mass matrix is enhanced compared with one in the type I and split seesaw cases. These are summarized as

$$\begin{cases} \Psi_{R_i}^{(0)}(x, y) = g_i e^{-m_i y} \psi_{R_i}^{(0)}(x) & \text{for the localization of the 5D wave functions} \\ S \supset -\delta(y - \ell) \frac{(\tilde{M}_R)_{ij}}{2} \overline{\Psi_{R_i}^{(0)c}} \Psi_{R_j}^{(0)} & \text{for the localization of the Majorana mass matrix} \end{cases}, \quad (21)$$

and

$$\begin{cases} (M_R)_{ij} = f_i f_j (\tilde{M}_R)_{ij} & \text{for the 4D Majorana mass matrix} \\ (y_\nu)_{i\alpha} = g_i (\tilde{y}_\nu)_{i\alpha} & \text{for the 4D neutrino Yukawa coupling matrix} \\ M_\nu = \tilde{y}_\nu^T E \tilde{M}_R^{-1} E \tilde{y}_\nu v^2 & \text{for the light (active) neutrino mass matrix} \end{cases}. \quad (22)$$

### 3.3 Localized right-handed neutrinos and Majorana masses at hidden brane

Next, we investigate the  $(H, H)$  case, i.e. both wave functions and Majorana masses of the right-handed neutrinos are localized at the hidden brane. The 5D wave function profiles of the right-handed neutrinos are given by (7). Then the relevant action is described by

$$S = \int d^4x \int_0^\ell dy \left[ M \left( i \overline{\Psi_{R_i}^{(0)}} \Gamma^A \partial_A \Psi_{R_i}^{(0)} + m_i \overline{\Psi_{R_i}^{(0)}} \Psi_{R_i}^{(0)} \right) - \left( \delta(y) (\tilde{y}_\nu)_{i\alpha} \overline{\Psi_{R_i}^{(0)}} L_\alpha \phi + \delta(y - \ell) \frac{(\tilde{M}_R)_{ij}}{2} \overline{\Psi_{R_i}^{(0)c}} \Psi_{R_j}^{(0)} + \text{h.c.} \right) \right]. \quad (23)$$



Inserting (7) into (23), we can find

$$\begin{cases} \Psi_{R_i}^{(0)}(x, y) = f_i e^{m_i y} \psi_{R_i}^{(0)}(x) & \text{for the localization of the 5D wave functions} \\ S \supset -\delta(y - \ell) \frac{(\tilde{M}_R)_{ij}}{2} \Psi_{R_i}^{(0)c} \Psi_{R_j}^{(0)} & \text{for the localization of the Majorana mass matrix} \end{cases}, \quad (24)$$

as the setup, and

$$\begin{cases} (M_R)_{ij} = g_i g_j (\tilde{M}_R)_{ij} & \text{for the 4D Majorana mass matrix} \\ (y_\nu)_{i\alpha} = f_i (\tilde{y}_\nu)_{i\alpha} & \text{for the 4D neutrino Yukawa coupling matrix} \\ M_\nu = \tilde{y}_\nu^T E^{-1} \tilde{M}_R^{-1} E^{-1} \tilde{y}_\nu v^2 & \text{for the light (active) neutrino mass matrix} \end{cases}, \quad (25)$$

as the results. It is seen that the 4D Majorana masses are not including exponential suppression factors, and thus this  $(H, H)$  case requires some mass scales for the right-handed neutrino sector in order to realize strongly hierarchical mass spectra. For the 4D neutrino Yukawa coupling, it is suppressed by  $f_i$  as well as the split seesaw case  $(H, S)$ . The resultant active neutrino mass matrix is including a suppression factor  $E^{-1}$  ( $(E^{-1})_{ij} = \delta_{ij} e^{-m_i \ell}$ ) compared to the type I and split seesaw mechanisms.

### 3.4 Localized right-handed neutrinos and Majorana masses at SM brane

Finally, we show the  $(S, S)$  case, i.e. both wave functions and Majorana masses of the right-handed neutrinos are localized at the SM brane. The 5D wave function profiles of the right-handed neutrinos are given by (18) and the relevant action is described by

$$S = \int d^4x \int_0^\ell dy \left[ M \left( i \overline{\Psi_{R_i}^{(0)}} \Gamma^A \partial_A \Psi_{R_i}^{(0)} - m_i \overline{\Psi_{R_i}^{(0)}} \Psi_{R_i}^{(0)} \right) - \delta(y) \left( (\tilde{y}_\nu)_{i\alpha} \overline{\Psi_{R_i}^{(0)}} L_\alpha \phi + \frac{(\tilde{M}_R)_{ij}}{2} \overline{\Psi_{R_i}^{(0)c}} \Psi_{R_j}^{(0)} + \text{h.c.} \right) \right]. \quad (26)$$

Substituting (18) into (26), we can find

$$\begin{cases} \Psi_{R_i}^{(0)}(x, y) = g_i e^{-m_i y} \psi_{R_i}^{(0)}(x) & \text{for the localization of the 5D wave functions} \\ S \supset -\delta(y) \frac{(\tilde{M}_R)_{ij}}{2} \Psi_{R_i}^{(0)c} \Psi_{R_j}^{(0)} & \text{for the localization of the Majorana mass matrix} \end{cases}, \quad (27)$$

as the setup, and

$$\begin{cases} (M_R)_{ij} = g_i g_j (\tilde{M}_R)_{ij} & \text{for the 4D Majorana mass matrix} \\ (y_\nu)_{i\alpha} = g_i (\tilde{y}_\nu)_{i\alpha} & \text{for the 4D Yukawa coupling matrix} \\ M_\nu = \tilde{y}_\nu^T \tilde{M}_R^{-1} \tilde{y}_\nu v^2 & \text{for the light (active) neutrino mass matrix} \end{cases}, \quad (28)$$

as the results. It can be seen that both 4D Majorana masses of the right-handed neutrinos and the neutrino Yukawa couplings are not suppressed because of the factor  $g_i$  (if  $m_i \ell \gg 1$ ), and the active neutrino mass matrix is described by the same formula as one in the type I and split seesaw mechanisms. Therefore, this  $(S, S)$  case is similar to the type I seesaw because of the localizations of the wave functions and Majorana masses at the SM brane.

## 4 Separate seesaw

We propose a new seesaw model by the use of the above results. A fundamental assumption in this seesaw model is that each generation of the right-handed neutrinos can have different localizations of the 5D wave function and Majorana mass, e.g. one of generations of the right-handed neutrinos has  $(H, S)$  localization and the others have  $(S, H)$  localization. This means that the localizations of  $(\Psi_R^{(0)}, \tilde{M}_R)$  are separated for each generation of the right-handed neutrinos. Under this assumption, when one introduces two generations of the right-handed neutrinos into the SM, one can consider 10 possible combinations of the localizations,<sup>2</sup> e.g.  $((\Psi_{R_1}^{(0)}, \tilde{M}_{R_1}), (\Psi_{R_2}^{(0)}, \tilde{M}_{R_2})) = ((H, S), (H, S)), ((H, S), (S, H)), ((H, S), (H, H)), ((H, S), (S, S)),$  and  $((S, H), (S, H))$  etc. where  $\tilde{M}_{R_i}$  is a fundamental mass scale of  $i$ -th generation of the right-handed neutrinos in a 5D action with a diagonal basis of 5D Dirac mass matrix. Therefore, in this seesaw model,  $\tilde{M}_R$  is not generically matrix. In this work, we investigate a combination and its results as an example, which will be interestingly applied to DM and baryogenesis models with respect to a left-right mixing angle as we will see later.

We consider the case of  $((\Psi_{R_1}^{(0)}, \tilde{M}_{R_1}), (\Psi_{R_2}^{(0)}, \tilde{M}_{R_2})) = ((H, S), (S, H))$  as an example with two generations of the right-handed neutrinos for simplicity. Relevant action for this case of *separate* seesaw is given by

$$S = \int d^4x \int_0^\ell dy \left[ M \left\{ i \overline{\Psi_{R_i}^{(0)}} \Gamma^A \partial_A \Psi_{R_i}^{(0)} + \left( m_1 \overline{\Psi_{R_1}^{(0)}} \Psi_{R_1}^{(0)} - m_2 \overline{\Psi_{R_2}^{(0)}} \Psi_{R_2}^{(0)} \right) \right\} \right. \\ \left. - \left\{ \delta(y) \left( (\tilde{y}_\nu)_{i\alpha} \overline{\Psi_{R_i}^{(0)}} L_\alpha \phi + \frac{\tilde{M}_1}{2} \overline{\Psi_{R_1}^{(0)c}} \Psi_{R_1}^{(0)} \right) + \delta(y - \ell) \frac{\tilde{M}_2}{2} \overline{\Psi_{R_2}^{(0)c}} \Psi_{R_2}^{(0)} + \text{h.c.} \right\} \right], \quad (29)$$

where  $i = 1, 2$  and  $\tilde{M}_i$  are fundamental mass scales of each generation of right-handed neutrinos. Note that the Majorana masses of the right-handed neutrinos ( $\tilde{M}_i$ ) in this action are not described by a matrix form because of the separate localizations at different branes. Solutions of 5D Dirac equations from this action determine extra-dimensional wave function profiles of the right-handed neutrinos as

$$\Psi_{R_1}^{(0)}(x, y) = f_1 e^{m_1 y} \psi_{R_1}^{(0)}(x), \quad \Psi_{R_2}^{(0)}(x, y) = g_2 e^{-m_2 y} \psi_{R_2}^{(0)}(x). \quad (30)$$

Then the resultant 4D Majorana masses, 4D Yukawa coupling matrices, and the light neu-

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<sup>2</sup>Here we do not consider an ordering of generations, that is, for instance we do not distinguish  $((H, S), (S, H))$  case with  $((S, H), (H, S))$  one. There are 24 possible combinations for the localizations in the case of three generations of the right-handed neutrinos.

trino mass matrix after the separate seesaw are written down as

$$M_i = f_i^2 \tilde{M}_i, \quad (31)$$

$$(y_\nu)_{1\alpha} = f_1 (\tilde{y}_\nu)_{1\alpha}, \quad (y_\nu)_{2\alpha} = g_2 (\tilde{y}_\nu)_{2\alpha}, \quad (32)$$

$$(M_\nu)_{\alpha\beta} = ((\tilde{y}_\nu)_{1\alpha} (\tilde{y}_\nu)_{1\beta} \tilde{M}_1^{-1} + e^{2m_2\ell} (\tilde{y}_\nu)_{2\alpha} (\tilde{y}_\nu)_{2\beta} \tilde{M}_2^{-1}) v^2, \quad (33)$$

where  $\alpha, \beta = e, \mu, \tau$ . After diagonalizing the light neutrino mass matrix  $M_\nu$ , one can obtain three mass eigenvalues of the light neutrinos as

$$m_{\nu 1} = 0, \quad m_{\nu 2} \simeq \mathcal{O}(|(\tilde{y}_\nu)_{1\alpha}|^2 v^2 \tilde{M}_R^{-1}), \quad m_{\nu 3} \simeq \mathcal{O}(e^{2m_2\ell} |(\tilde{y}_\nu)_{2\alpha}|^2 v^2 \tilde{M}_R^{-1}), \quad (34)$$

where we assume  $|(\tilde{y}_\nu)_{i\alpha}| \simeq |(\tilde{y}_\nu)_{i\beta}|$  ( $\alpha \neq \beta$ ) and take  $\tilde{M}_R$ , which is a fundamental mass scale of the right-handed neutrino sector in the action, as  $\tilde{M}_R \simeq \tilde{M}_1 \simeq \tilde{M}_2$ . Note that this kind of separate seesaw can lead to hierarchical mass eigenvalues of the light neutrinos, which are determined by exponential factors, due to different localizations of the wave function and Majorana mass for each generation of the right-handed neutrinos unlike the type I and split seesaw mechanisms. This model can also realize hierarchical mass spectra of the right-handed neutrinos and the neutrino Yukawa couplings among each generation of the right-handed neutrinos. Other combinations of localizations lead to different patterns of mass spectra of the light neutrinos and the right-handed neutrinos, and neutrino Yukawa couplings for each generation. Such formalism for all cases and extensions to three generations of the right-handed neutrinos models are straightforward. We now concentrate on this type of separate seesaw,  $((\Psi_{R_1}^{(0)}, \tilde{M}_{R_1}), (\Psi_{R_2}^{(0)}, \tilde{M}_{R_2})) = ((H, S), (S, H))$ , and apply it to realistic models of neutrino DM and baryogenesis with three generations of the right-handed neutrinos in the next section.

## 5 Applications to models of dark matter and baryogenesis

In this section, we apply the separate seesaw to models of neutrino DM with baryogenesis. It is known that a sterile neutrino with keV scale mass can be a candidate for DM. Further, models with three generations of the right-handed neutrinos including keV sterile neutrino can simultaneously explain the BAU, tiny active neutrino mass scale, and LSND/MiniBooNE anomaly in addition to the DM [12, 15, 16, 17]. In such kind of models, the tiny active neutrino mass is described by the type I seesaw formula, and the models can be embedded into the split seesaw mechanism in order to realize split mass spectra without introducing strongly hierarchical mass scales. However, it is also known that in such models with the

keV sterile neutrino, the sterile neutrino (with keV mass) should not contribute to the active neutrino masses to satisfy cosmological ( $X$ -ray) bounds on a left-right mixing (neutrino Yukawa couplings) for the keV sterile neutrino as

$$\theta^2 \equiv \sum \frac{|(y_\nu)_{1\alpha}|^2 v^2}{M_1^2} \lesssim \mathcal{O}(10^{-11} - 10^{-9}), \quad (35)$$

in a mass region of the sterile neutrino as  $\mathcal{O}(1) \text{ keV} \lesssim M_s (\equiv M_1) \lesssim \mathcal{O}(10) \text{ keV}$  (e.g. see [10] and references therein). This cosmological bound means that the resultant neutrino mass,  $m_{\nu 1}$ , from the keV sterile neutrino after the seesaw mechanism is much smaller than solar and atmospheric neutrino mass scales as  $m_{\nu 1} \ll m_{\text{sol}} < m_{\text{atm}}$  where  $m_{\text{sol}} \simeq 8.73 \times 10^{-3} \text{ eV}$  and  $m_{\text{atm}} \simeq 5.05 \times 10^{-2} \text{ eV}$  [28]. In other words, once the keV sterile neutrino contributes to the active neutrino mass through the seesaw mechanism, the model is conflict with the cosmological bound because of a large left-right mixing angle,

$$\theta^2 = \sum \frac{|(y_\nu)_{1\alpha}|^2 v^2}{M_1^2} \simeq \frac{m_{\text{sol(atm)}}}{M_s} \simeq \mathcal{O}(10^{-6} - 10^{-5}). \quad (36)$$

Therefore, in a realistic model with such keV sterile neutrino DM, an additional suppression for  $\theta$  (equivalently to  $|(y_\nu)_{1\alpha}|$ ) is needed to be consistent with the cosmological constraint. Further, at least two more generations of the right-handed neutrinos are required to reproduce the solar and atmospheric neutrino mass scales. Such situation is realized by taking the Yukawa couplings of the keV sterile neutrino to be additionally small compared to ones of the other two sterile neutrinos, which give the solar and atmospheric neutrino mass scales, in some models with keV sterile neutrino DM. The separate seesaw can lead to the additional suppression for the left-right mixing angle (the Yukawa couplings) and give a typical mass spectrum of active neutrinos as  $m_{\nu 1} \ll m_{\nu 2} (\simeq m_{\text{sol}}) < m_{\nu 3} (\simeq m_{\text{atm}})$  in the keV sterile neutrino DM models.

In order to see it, we extend the separate seesaw with two generations of the right-handed neutrinos given in the previous section to the three generations case. The relevant Lagrangian is given by

$$S = \int d^4x \int_0^\ell dy \left[ M \left\{ i \overline{\Psi}_{R_i}^{(0)} \Gamma^A \partial_A \Psi_{R_i}^{(0)} + \left( m_1 \overline{\Psi}_{R_1}^{(0)} \Psi_{R_1}^{(0)} - m_j \overline{\Psi}_{R_j}^{(0)} \Psi_{R_j}^{(0)} \right) \right\} \right. \\ \left. - \left\{ \delta(y) \left( (\tilde{y}_\nu)_{i\alpha} \overline{\Psi}_{R_i}^{(0)} L_\alpha \phi + \frac{\tilde{M}_1}{2} \overline{\Psi}_{R_1}^{(0)c} \Psi_{R_1}^{(0)} \right) + \delta(y - \ell) \frac{\tilde{M}_j}{2} \overline{\Psi}_{R_j}^{(0)c} \Psi_{R_j}^{(0)} + \text{h.c.} \right\} \right], \quad (37)$$

where  $i = 1, 2, 3$ ,  $j = 2, 3$ , and we assume that the Hidden brane localized Majorana masses are described by a  $2 \times 2$  diagonal mass matrix,  $\tilde{M}_R = \text{Diag}\{\tilde{M}_2, \tilde{M}_3\}$ , for simplicity. Note that

this is an extension of  $((\Psi_{R_1}^{(0)}, \tilde{M}_{R_1}), (\Psi_{R_2}^{(0)}, \tilde{M}_{R_2})) = ((H, S), (S, H))$  case to the three generation,  $((\Psi_{R_1}^{(0)}, \tilde{M}_{R_1}), (\Psi_{R_j}^{(0)}, \tilde{M}_{R_j})) = ((H, S), (S, H))$ . In a similar manner to the two generation case, we obtain extra-dimensional wave function profiles of the right-handed neutrinos as

$$\Psi_{R_1}^{(0)}(x, y) = f_1 e^{m_1 y} \psi_{R_1}^{(0)}(x), \quad \Psi_{R_j}^{(0)}(x, y) = g_j e^{-m_j y} \psi_{R_j}^{(0)}(x), \quad (38)$$

and read the resultant 4D Majorana masses, 4D neutrino Yukawa coupling matrices, the light neutrinos mass matrix, and three mass eigenvalues of light neutrinos as

$$M_i = f_i^2 \tilde{M}_i, \quad (39)$$

$$(y_\nu)_{1\alpha} = f_1 (\tilde{y}_\nu)_{1\alpha}, \quad (y_\nu)_{j\alpha} = g_j (\tilde{y}_\nu)_{j\alpha}, \quad (40)$$

$$(M_\nu)_{\alpha\beta} = \left( (\tilde{y}_\nu)_{1\alpha} (\tilde{y}_\nu)_{1\beta} \tilde{M}_1^{-1} + \sum_{j=2,3} e^{2m_j \ell} (\tilde{y}_\nu)_{j\alpha} (\tilde{y}_\nu)_{j\beta} \tilde{M}_j^{-1} \right) v^2, \quad (41)$$

$$m_{\nu 1} \simeq \mathcal{O}(|(\tilde{y}_\nu)_{1\alpha}|^2 v^2 \tilde{M}_1^{-1}), \quad m_{\nu j} \simeq \mathcal{O}(e^{2m_j \ell} |(\tilde{y}_\nu)_{j\alpha}|^2 v^2 \tilde{M}_j^{-1}), \quad (42)$$

respectively. This separate seesaw can realize strongly hierarchical mass spectra of the sterile neutrinos and neutrino Yukawa couplings among the 1st and the other generations of right-handed neutrinos. As the results, one of three neutrino mass eigenvalues  $m_{\nu 1}$  is suppressed from the other two mass eigenvalues  $m_{\nu j}$ . In a realistic model, these two mass eigenvalues are of order solar and atmospheric scales,  $m_{\nu j} \sim m_{\text{sol(atm)}}$ . However, in the expressions of the mass eigenvalues  $m_{\nu j}$ , an exponential factor  $e^{2m_j \ell}$  appears while  $m_{\nu 1}$  does not include the factor. This affects on an evaluation of the left-right mixing as

$$\theta^2 = \sum \frac{|(y_\nu)_{1\alpha}|^2 v^2}{M_1^2} \simeq \frac{m_{\text{sol(atm)}}}{e^{2m_j \ell} M_s}, \quad (43)$$

where we assume that all  $|(\tilde{y}_\nu)_{i\alpha}|$  are the same order and  $\tilde{M}_R \simeq \tilde{M}_i$ .

We apply this separate seesaw to two typical mass spectra of the sterile neutrinos, which can give the sterile neutrino DM and generate the BAU in addition to the tiny active neutrino mass scales. The first example of the mass spectra is

$$(M_1, M_2, M_3) \sim (\mathcal{O}(\text{keV}), \mathcal{O}(10^{11} \text{ GeV}), \mathcal{O}(10^{12} \text{ GeV})). \quad (44)$$

In this type of model, the lightest sterile neutrino with the keV mass is a DM and heavy sterile neutrinos with the intermediate mass scale can lead to the BAU via leptogenesis as mentioned in the split seesaw mechanism. This mass spectrum of the sterile neutrinos requires the corresponding neutrino Yukawa couplings  $|(y_\nu)_{j\alpha}|$  of order  $|(y_\nu)_{j\alpha}| \simeq \sqrt{m_{\text{sol(atm)}} \tilde{M}_j} / v \sim \mathcal{O}(10^{-2} - 10^{-1})$  as known in the canonical type I seesaw mechanism. In our realization by the separate seesaw, when we take  $(m_1 \ell, m_2 \ell, m_3 \ell) \simeq (23.3, 3.64, 2.26)$ ,  $M = 5 \times 10^{17} \text{ GeV}$ ,

$\ell^{-1} = 10^{16}$  GeV,  $\tilde{M}_R = \tilde{M}_i = 10^{15}$  GeV, and  $|(\tilde{y}_\nu)_{i\alpha}| \simeq (5 - 10) \times 10^{-2}$ , the model lead to a mass spectrum (44), and the solar and atmospheric neutrino mass scales. Further, an additional suppression for the left-right mixing angle can be naturally realized as shown in (43),  $\theta^2 \sim \mathcal{O}(10^{-10})$ , which is consistent with the cosmological bound. In this realization, the mass scales in the model are super heavy  $\mathcal{O}(10^{15-17})$  GeV or the EW scale.

The next application of the separate seesaw is to a model with a mass spectrum of the sterile neutrinos as

$$(M_1, M_2, M_3) \sim (\mathcal{O}(\text{keV}), \mathcal{O}(10 \text{ GeV}), \mathcal{O}(10 \text{ GeV})). \quad (45)$$

This type of model can explain the BAU through a mechanism proposed in [29] i.e. an oscillation between the 2nd and 3rd generations of the right-handed neutrinos. The model described by the mass spectrum (45) is known as the  $\nu$ MSM [12], which can also realize the tiny active neutrino masses through the seesaw mechanism by utilizing heavier two sterile neutrinos. Since this model also includes the keV sterile neutrino DM, the model should require an additional suppression for the left-right mixing (neutrino Yukawa couplings) of the keV sterile neutrino to satisfy cosmological bound as well as the previous example. In a realization from the separate seesaw, when we take  $(m_1\ell, m_2\ell, m_3\ell) \simeq (23.3, 15.9, 15.9)$ ,  $M = 5 \times 10^{17}$  GeV,  $\ell^{-1} = 10^{16}$  GeV,  $\tilde{M}_R = \tilde{M}_i = 10^{15}$  GeV, and  $|\tilde{y}_{j\alpha}| \simeq \mathcal{O}(10^{-7})$ , the model can lead to a mass spectrum (45) and  $\theta^2 < \mathcal{O}(10^{-11})$  in addition to both the solar and atmospheric neutrino mass scales.<sup>3</sup>

## 6 Summary

The introduction of the right-handed neutrinos into the SM can solve several problems in the particle physics and cosmology such as the DM, the generation of the BAU, the neutrino anomaly, and the realization of the small active neutrino mass through the seesaw mechanism. Further, extra-dimensional theories can also lead to various interesting results for phenomenology. In this work, we have focused on the case that only the right-handed neutrinos live in the flat 5D space. In particular, the localizations of the extra-dimensional wave functions and Majorana masses of the right-handed neutrinos, and the results for relevant parameters to the neutrino masses have been investigated. First, it has been shown that different localizations of the wave functions and Majorana masses of the right-handed

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<sup>3</sup>We have taken smaller values of neutrino Yukawa couplings in the action as  $|\tilde{y}_{j\alpha}| \simeq \mathcal{O}(10^{-7})$ , which are the same as ones required in the  $\nu$ MSM for the Yukawa couplings of 2nd and 3rd generations of right-handed neutrinos. The split seesaw does not need such tiny Yukawa couplings in the action for the heavier right-handed neutrinos but this separate seesaw must require them. Therefore, an additional mechanism to give such tiny Yukawa couplings, e.g. Froggatt-Nielsen mechanism [19], should be introduced.

neutrinos in the extra-dimension lead to different suppression factor dependences of the effective Majorana neutrino masses and the neutrino Yukawa couplings.

Next, a new extra-dimensional seesaw model has been proposed by combining the above results. A fundamental assumption of the new seesaw is that each generation of the right-handed neutrinos has different localizations of the wave function and Majorana masses in the extra-dimension. As the results, the Majorana neutrino masses and the neutrino Yukawa couplings for each generation can be different with ones of the canonical type I seesaw and the split seesaw mechanisms. We have shown the results of the case,  $((\Psi_{R_1}^{(0)}, \tilde{M}_{R_1}), (\Psi_{R_2}^{(0)}, \tilde{M}_{R_2})) = ((H, S), (S, H))$ , as an example for the case of two generations of right-handed neutrinos. It has been found that this case of separate seesaw model can lead to hierarchical mass eigenvalues of the light neutrinos, which are determined by exponential factors, due to different localizations of wave function and Majorana masses for each generation of the right-handed neutrinos unlike the type I and split seesaw mechanisms. Further, it has been also shown that this model can realize hierarchical mass spectra of the right-handed neutrinos and the neutrino Yukawa couplings among each generation of the right-handed neutrinos.

Finally, we have applied the results of the separate seesaw to models of the keV sterile neutrino DM with baryogenesis. It has been known that an additional suppression for the left-right mixing angle of the keV sterile neutrino is needed to be consistent with the cosmological constraint in the framework of the seesaw mechanism. We have shown that the above separate seesaw extended to the three generations of the right-handed neutrinos can naturally realize the additional suppression for the mixing and be favored in two typical models of the keV sterile neutrino DM with baryogenesis.

At the end of the paper, we comment on realizations of leptonic mixing angles determined by the neutrino oscillations experiments. The separate seesaw can be consistent with two possible discussions to obtain experimentally observed values of leptonic mixing angles, i.e. a discussion of  $A_4$  flavor models in the split seesaw mechanism [16] and a minimal neutrino texture analysis for the model with the keV sterile neutrino DM [30]. The fundamental assumption of the separate seesaw might be also interesting for the other phenomenological applications and/or other types of seesaw mechanism such as a radiative seesaw model [31]. The applications will be presented in a different publication [32].

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